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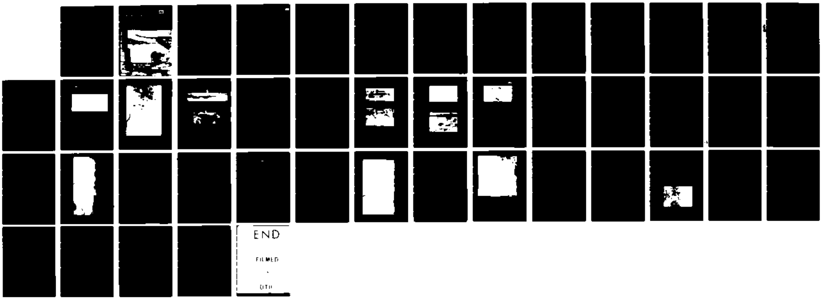

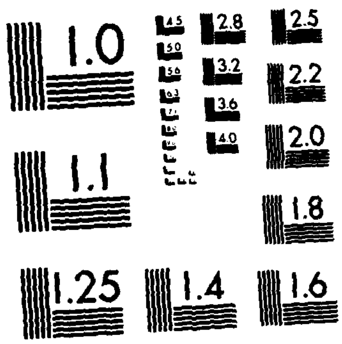

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CRREL REPORT 82-36

US Army Corps of Engineers
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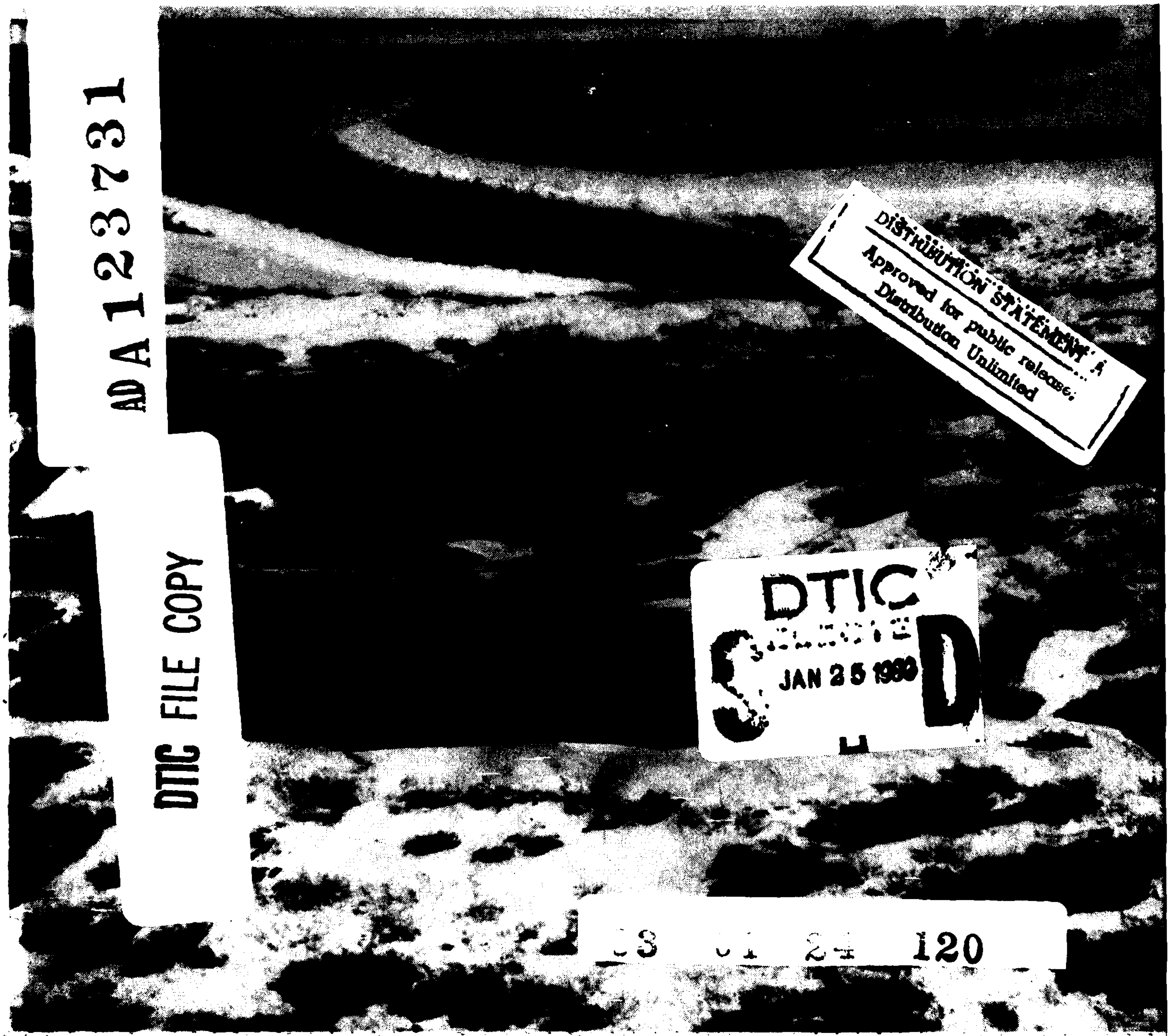
Long-term modifications of perennially frozen sediment and terrain at East Oumalik, northern Alaska



Cover: Thermokarst topography of the disturbed East Oumalik upland drill site in 1980. Drill rig platform was located on the low relief surface at left center. Linear depressions lie where timber beams were located. Depressions partially filled with snow mark former bulldozed roads. Receiving and supply storage platform on steel barrels was located in foreground. (Photograph by D. Lawson.)

CRREL Report 82-36

November 1982

Long-term modifications of perennially frozen sediment and terrain at East Oumalik, northern Alaska

Daniel E. Lawson

Prepared for
U.S. GEOLOGICAL SURVEY

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Camp construction and drilling activities in 1950 at the East Oumalik drill site in northern Alaska caused extensive degradation of ice-rich, perennially frozen silt and irreversible modification of the upland terrain. In a study of the long-term degradational effects at this site, the near-surface geology was defined by drilling and coring 76 holes (maximum depth of 34 m) in disturbed and undisturbed areas and by laboratory analyses of these cores. Terrain disturbances, including bulldozed roads and excavations, camp structures and off-road vehicle trails, were found to have severely disrupted the site's thermal regime. This led to a thickening of the active layer, melting of the ground ice, thaw subsidence and thaw consolidation of the sediments. Slumps, sediment gravity flows and collapse of materials on slopes bounding thaw depressions expanded the degradation laterally, with thermal and hydraulic erosion removing

20. Abstract (cont'd).

material as the depressions widened and deepened with time. Degradational processes became less active after thawed sediments thickened sufficiently to slow the increase in the depth of thaw and permit slope stabilization. The site's terrain is now irregular and hummocky with numerous depressions. Seasonal thaw depths are deeper in disturbed areas than in undisturbed areas and reflect the new moisture conditions and morphology. The severity of disturbance is much greater at East Oumalik than at another old drill site, Fish Creek. The difference results primarily from differences in the physical properties of the sediments, including the quantity and distribution of ground ice. In areas similar to East Oumalik, the removal or severe compaction of the vegetative mat would cause similar adverse physical changes to take place over two to three decades and should therefore be avoided.

PREFACE

This report was prepared by Dr. Daniel E. Lawson, Research Physical Scientist, of the Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. It is based upon field research in northern Alaska and laboratory studies in Hanover that were conducted from 1977 to 1981.

This research was funded by the U.S. Geological Survey under the National Petroleum Reserve-Alaska (NPRA) program. The author thanks Dr. Max C. Brewer, Dr. John Haugh and James Stout of the Office of the NPRA for their assistance and enthusiastic support of this project, and the many personnel at Camp Lonely in the NPRA who provided continuous logistical support. The author thanks Daniel Crowner, William Davies and Richard Mead who assisted in the field, Dr. Jerry Brown, Dr. L. David Carter, Frederick Crory, Dr. K.R. Everett, Oscar J. Ferrians, Lawrence Gatto and Paul Sellmann for their helpful critical reviews of this manuscript, Eleanor Huke for drafting the figures and Edmund Wright for editing the report.

The author especially thanks Bruce Brockett for his enthusiastic assistance in the field, his perseverance in operating the drill rig and obtaining core of the permafrost under sometimes very trying conditions, and his discussions of the research.

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SUMMARY

Camp construction and drilling activities that took place during approximately 10 months in 1950/1951 at the East Oumalik drill site in northern Alaska initiated extensive degradation of ice-rich permafrost and irreversible modification of about 3.5 km^2 of the terrain. Certain degradational processes remained active along the southwestern margin of the site and at a few locations within the site in 1981. Such continuous, long-term modifications of permafrost terrain as the result of man's activities have not previously been documented.

The East Oumalik site was studied from 1978 to 1981 to determine the response of near-surface materials and processes to the drilling activities of 1950 and to define the degradational processes that modified the site to its present condition. Near-surface geology was defined mainly by field and laboratory analyses of disturbed and equivalent undisturbed parts of the upland. These analyses included coring 76 holes of 1.5- to 34-m depth within representative parts of the upland and also augering 360 holes of 1.5-m depth along transects across it. Frozen and thawed samples from the cores were analyzed for various physical attributes, such as grain size distribution, moisture content, ice volume and Atterberg limits. Similar analyses were made of material from another old drill site, Fish Creek, in order to compare the effects of disturbance with those at East Oumalik.

The East Oumalik drill site was established upon a moderately drained, low relief upland surface composed of perennially frozen, ice-rich silt. Terrain disturbances, such as bulldozing of roads, excavation, construction of camp structures, and off-road vehicle trafficking, disrupted the thermal regime of the frozen silt, causing thawing of the permafrost and a subsequent thickening of the active layer. Melting of the ground ice, which composes 42 to 90% by volume of the upper 15 m of the frozen silt, caused subsidence and initiated slumping, gravitational flow and collapse of slope material into the subsiding areas. Depressional areas became interconnected as lateral slope erosion and active layer thickening continued beneath individual disturbances. Thermal and hydraulic slope erosion was extensive in drainage ditches and wherever drainage channels formed within trails, wedge troughs and other sloping thaw depressions. Degradational processes were probably most active for 10 to 15 years after disturbance, with activity gradually diminishing to its present level.

Lateral erosion caused the impacted area to be larger than the area initially disturbed. Such lateral expansion was facilitated by the high ice content of the silt, the frequency and large dimensions of wedge ice, the instability of the silt upon thawing, and local variations in relief, including those that developed as thaw subsidence took place. At this site thawed silts are saturated to oversaturated and their water contents immediately after thawing are significantly greater than their liquid limits; furthermore, their liquidity index indicates that the materials are at failure upon thawing. Lateral expansion and deepening of subsiding areas apparently ceases only after enough sediment has been deposited in the thaw depression to retard thaw bulb expansion and permit slope stabilization. Deposition results when the drainage gradient between interconnected troughs is lost or when insufficient meltwater is available to remove the sediments sloughed into depressions by rapid headward erosion of degrading slopes.

The upland has been transformed from a low relief and relatively featureless surface into an irregular, hummocky surface with numerous depressions, many of which are filled with water year-round. Relief across the site was modified from less than 2 m to greater than 8 m, with individual depressions up to 5 m deep. Seasonal thaw depths mostly reflect the new topography and moisture conditions of the disturbed areas. They are generally deeper than in undisturbed terrain adjacent to the site, and they may not be in equilibrium with the modified terrain.

A comparison of the disturbances and degradational processes at East Oumalik to those at the Fish Creek drill site (175 km to the northeast) indicates that the severity of disturbance is greater at East Oumalik. This dissimilarity results primarily from differences in the physical properties of the near-surface sediment and terrain, and the types of degradational processes initiated because of these properties. In particular, the dimensions and volume of ground ice, mechanical properties of the sand and lower relief of the upland were critical factors limiting the physical modifications of Fish Creek to those that result from thaw subsidence and consolidation.

This study indicates that geotechnical investigations of the subsurface materials for selection of construction sites must include an analysis of the content and distribution of ground ice to determine the properties of the sediments upon thawing. The impact of disturbance at East Oumalik indicates that in morphologically similar areas of fine-grained, ice-rich sediments, adverse physical changes will take place over an extended period of about two to three decades if the vegetative mat is altered by either removal or severe compaction.

LONG-TERM MODIFICATIONS OF PERENNIALLY FROZEN SEDIMENT AND TERRAIN AT EAST OUMALIK, NORTHERN ALASKA

Daniel E. Lawson

INTRODUCTION

The impact of man's activities on the natural processes and properties of arctic tundra depends largely on the effect of these activities on the thermal regime at the ground surface. Most arctic regions are underlain by perennially frozen ground, which may contain substantial amounts of ice (e.g. Black 1969, Mackay and Black 1973, Sellmann et al. 1975, Pollard and French 1980). Disturbance of the tundra generally reduces the insulating effect of the vegetation and uppermost soil horizon, causing an increase in the mean annual temperature at the ground surface and thus in the annual depth of thaw (e.g. Muller 1947, Brown et al. 1969, Mackay 1970, Heginbottom 1971, Viereck 1973, Brown and Grave 1979). Melting of ice in the near-surface materials causes the ground surface to subside (e.g. Muller 1947, Terzaghi 1952).

Following disturbance of ice-rich tundra, thaw subsidence often modifies the drainage so that some areas remain wet for longer periods of time during the year while others become much drier. The increase in moisture collected in the active layer of depressional areas also results in greater heaving of the ground surface in winter when it freezes. Increased thaw may induce other thermokarst-related processes, such as the slump or flow of slope materials or the gullying and removal of sediment by erosion in areas with sufficient local or regional relief (e.g. Muller 1947, Ferrians et al. 1969, Mackay 1970, French and Egglinton 1973, How 1974, French 1974, McRoberts and Morgenstern 1974a, b, Lawson 1979). The distribution and volume of ice in near-surface materials are thus critical factors in determining the effect of disturbance on permafrost terrain. Because of the importance of these factors, Ives (1970) proposed that differences in the susceptibility of permafrost to damage by disturbance could be approximated as a ratio of the volume of ice in the permafrost to the mean annual ground temperature.

Although a number of studies have examined the short-term effects (about 10 years or less) of man's impact on permafrost terrain (e.g. Heginbottom 1973, Radforth 1973, Rickard and Brown 1974, French 1975, 1980, Berg and Smith 1976, Adam and Hernandez 1977, Abele et al. 1978), the response and recovery of permafrost terrain to disturbance after longer periods of time has been only poorly documented (Grave and Nekrasov 1962, Hernandez 1973, Isaacs 1974, Lawson et al. 1978, Lawson and Brown 1979). With the increase in development of arctic tundra regions, an understanding of the long-term effects is needed. This will allow a realistic appraisal of the terrain's sensitivity to future development and govern the techniques that must be utilized to prevent unwanted environmental changes.

Old drill sites in the Naval Petroleum Reserve Number 4 (PET-4), now designated the National Petroleum Researve-Alaska (NPRA) (Fig 1), provide examples of the effects of camp construction and drilling operations on permafrost terrain after approximately 30 years. From 1944 to 1953, the U.S. Navy drilled 36 exploratory wells in a variety of the geologic, topographic and climatic settings in PET-4 (Reed 1958).

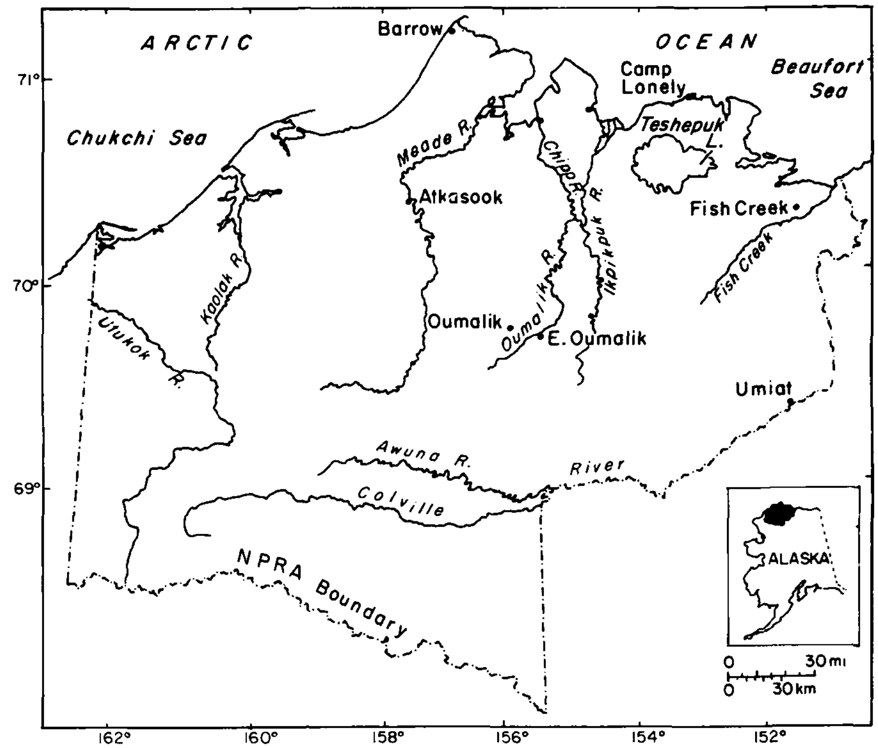


Figure 1. Location of the East Oumalik, Fish Creek and Oumalik drill sites in the NPRA.

From 1978 to 1981, I examined the effects of drilling activities that took place in 1950 at the East Oumalik drill site (69°47′ 29″ N, 155°32′39″ W). The primary objectives of this study were to analyze the response of the near-surface materials and surficial processes to those activities and define the degradational processes that modified the site to its present condition. The analyses indicate that various cryogenic and sedimentologic processes were initiated that have caused extensive modification of the thermal regime, ground surface and drainage of the site. Comparison with another PET-4 drill site, Fish Creek, indicates the importance of the properties of near-surface materials in determining the extent of physical modification that took place.

METHODOLOGY

Standard geological techniques were used to analyze the response of the East Oumalik site to disturbance in 1950-51. Details of the near-surface geology of the drill site prior to its occupation were defined mainly by field and laboratory analyses of equivalent undisturbed areas next to the camp and exploratory well. These areas were identified by comparing the terrain and vegetation of the site and that of adjacent areas on aerial photographs of the upland in 1948 and 1978. Because no observations were made on the site between 1951, when it was abandoned, and 1978, when this study began, the degradational processes had to be interpreted from the erosional effects and sedimentology of the deposits of these processes. Wherever possible, trenches were dug to examine the sedimentology of disturbed and undisturbed near-surface materials.

Near-surface sediment and soil of the active layer and perennially frozen ground in disturbed and undisturbed areas were sampled by coring. Drill holes were located upon representative surficial features and along transects across disturbed and undisturbed terrain. A total of 76 holes were cored to depths ranging from 1.5 to 34 m. An additional 360 holes of 1.5-m depth and spacing of 2 m were augered along two transects. Detailed results of the drilling program will be presented in a subsequent report in preparation.

The geology of each drill hole, including the type and distribution of visible ground ice, was logged. Frozen and thawed samples were selected for laboratory analyses that included grain size distribution, moisture content, ice volume, organic content by loss on ignition, bulk density, and liquid and plastic limits. These data were used to calculate various parameters such as degree of saturation, porosity, void ratio and textural statistics.

The site was surveyed using a self-leveling level and rod. Active layer thickness was measured by probing to refusal with a steel rod.

GEOLOGICAL SETTING

East Oumalik lies approximately 170 km south-southeast of Barrow, Alaska, near the center of the NPRA (Fig. 1) and just north of the boundary between the Arctic Coastal Plain and Arctic Foothills Provinces (Wahrhaftig 1965). This region is characterized by upland surfaces cut by meandering streams and active, often deeply incised, thaw lakes (Fig. 2). Relief between the uplands and valley bottoms, including drained lake basins, ranges from 3 to 20 m with slope angles of 5° to 15° (Johnson 1978). Sediments underlying the region are perennially frozen and consist mostly of Quaternary silt and fine-grained sand (Black 1964, Williams et al. 1978). Stratigraphic logs of the East Oumalik exploratory well indicate that bedrock lies at a depth of about 30 m beneath ice-rich silt that contains sporadic lenses or layers of fine sand or clay. These materials are continuously frozen to a depth of 267 m (U.S. Navy 1951).

The camp and exploratory well were established upon a mostly featureless, gently sloping and moderately drained upland surface (Fig. 3) that is bounded on three sides by slopes of stream valleys (Fig. 4). The main stream on the southern and western sides of the site is entrenched about 15 m and meanders northward to the Oumalik River. This valley bottom contains meander cutoffs, small drained lake basins and marshes (Fig. 4). Solifluction lobes lie on the lower half of the valley slopes. The beaded tributary stream on the northern margin of the site flows within the upland materials.

With the exception of linear patterns from vehicle tracks north of the site, disturbance resulting from man is not evident in the 1948 aerial photograph (Fig. 4). Thermokarst resulting from

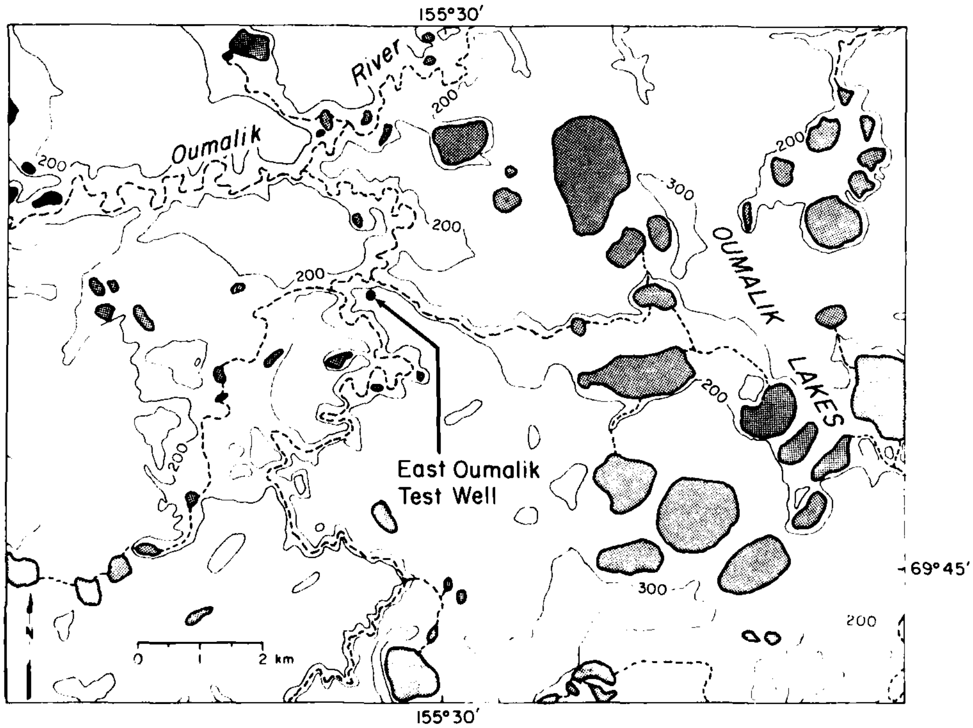


Figure 2. Topographic map of the region surrounding the East Oumalik drill site (from USGS Ikpikpuk River Quadrangle, 1956). Contour interval in feet.

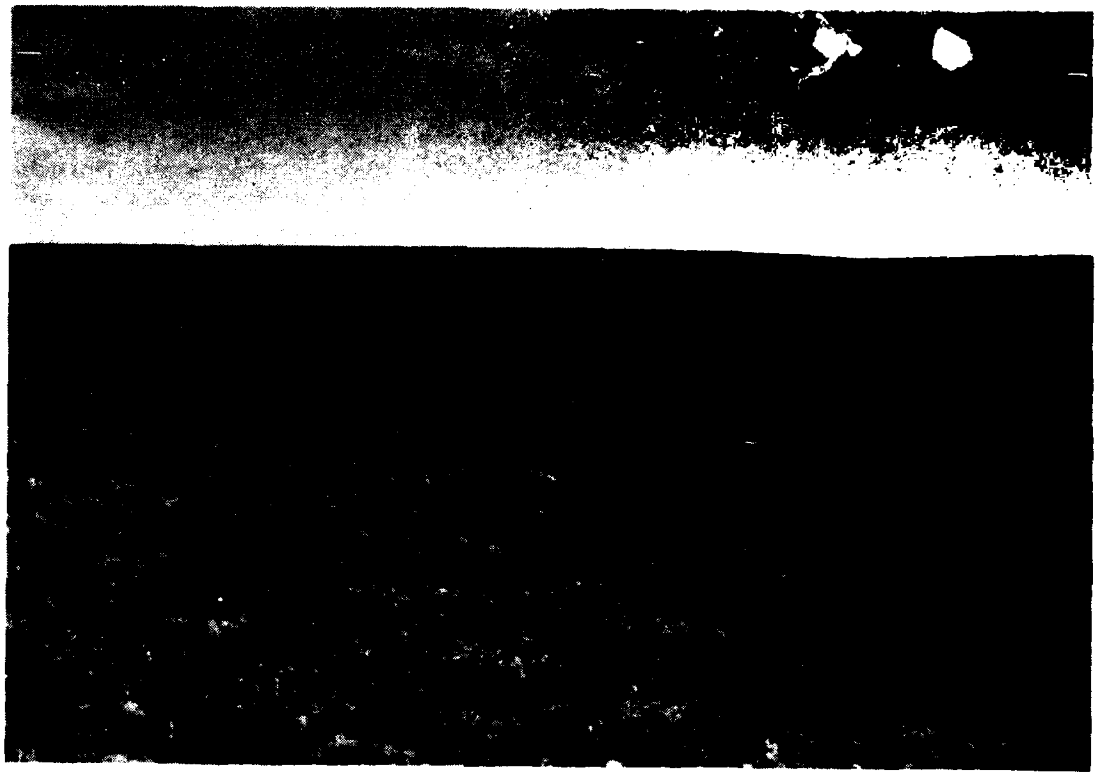


Figure 3. Undisturbed upland surface looking east of the former drill site in 1980.

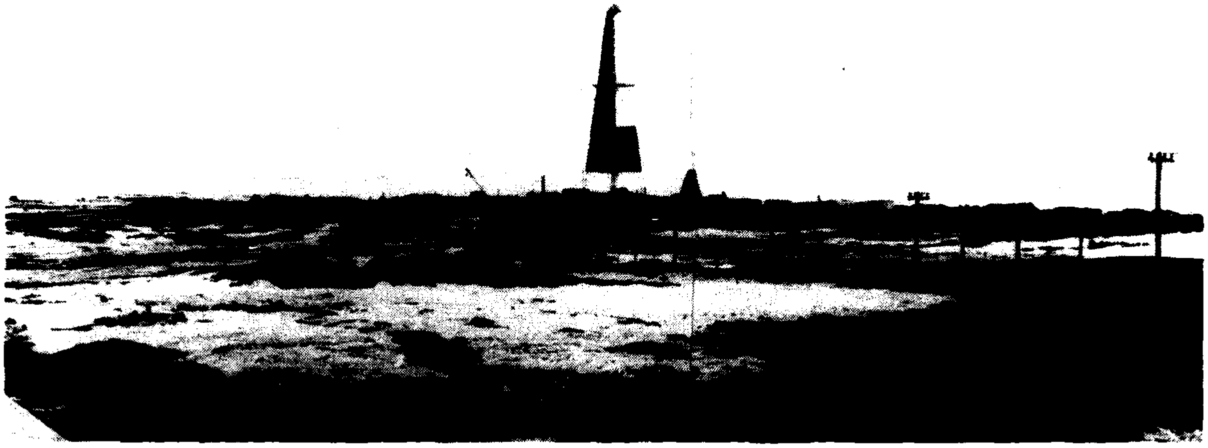
natural processes was more prevalent elsewhere on the uplands. Gully entrenchment, thermal erosion and other processes have modified the drainage and developed areas with well-defined polygonal trough patterns. A few locations in the region exhibit large areas of thermokarst next to valley slopes that are apparently still expanding laterally into upland sediments. Retrogressive slumps and flows have modified valley-marginal sediments at other locations. Such features indicate the presence of frozen sediments with relatively high ice contents and thus their potential susceptibility to reworking by thermokarst processes if disturbed (e.g. French 1975).

Livingstone et al. (1958) used the process of thaw lake formation (e.g. Black 1969, Tedrow 1969) to estimate the quantity of ground ice that melted during the formation of a thaw lake in upland sediments located about 6 km east of the East Oumalik site. They estimated that ground ice composed 68% by volume of the upper 28 m of sediment in which the lake formed. Williams and Yeend (1979) similarly estimated that a drained thaw lake near Umiat had developed in perennially frozen silt containing 78% ground ice by volume. Both estimates are comparable to the values I measured in samples analyzed for this study.

CAMP CONSTRUCTION AND OCCUPATION

The East Oumalik site was constructed and subsequently occupied from April 1950 through mid-January 1951. The drill rig, camp buildings and other equipment were moved overland from the Oumalik drill site (Fig. 1) by sled-train during April and May of 1950 (Reed 1958). Supplies were also freighted on C46's and C54's during April from Barrow to an airstrip located on a frozen lake about 5 km from the East Oumalik site. Camp construction began shortly thereafter, with the well being spudded on 23 October 1950. Drilling continued until 30 December 1950 with the hole officially abandoned on 7 January 1951. The camp was then dismantled and the equipment freighted by sled-train to Barrow over the Oumalik trail (a main artery between Barrow and Umiat which passed through the site).

Figure 4. Aerial photograph of the East Oumalik drill site on 6 September 1948 (BAR-124-147) prior to occupation. Dashed line marks the camp boundary; black line outlines approximate area of activities. Examples of natural thermokarst in the region include (1) headward expansion and deepening of small gullies by thermal and mechanical erosion, (2) slump and flow of valley-marginal sediments, and (3) degrading upland materials next to a thaw lake.



a. Drilling rig.

b. Derrick, camp buildings and other equipment used at East Oumalik.

Figure 5. Equipment in use in 1949 at the Oumalik drill site before tear-down and transport to the East Oumalik site in 1950.

The principal camp structures were 6.1- × 12.2-m (20- × 40-ft) Quonset huts used for a mess hall, a galley, an oilfield warehouse, a recreation hall and sleeping quarters; a Jamesway hut also used for sleeping quarters; and 11 wanigans used for offices, shops, sleeping quarters, a latrine, and water and equipment storage (Fig. 5). Buildings were supported by 1.2-m to 2.0-m-long wood or steel piles driven into the permafrost. Boardwalks, also on piles, joined many of the buildings.

Drilling equipment included a Wilson Super Titan rig, Ideco derrick and associated equipment such as boilers, generators, cementing units and mud and water tanks (Fig. 5). Vehicles used on the site included two weasels, an LVT, a D-8 Caterpillar dozer, a D-6 Caterpillar dozer, a TD-9 cherry picker, a Northwest crane and a

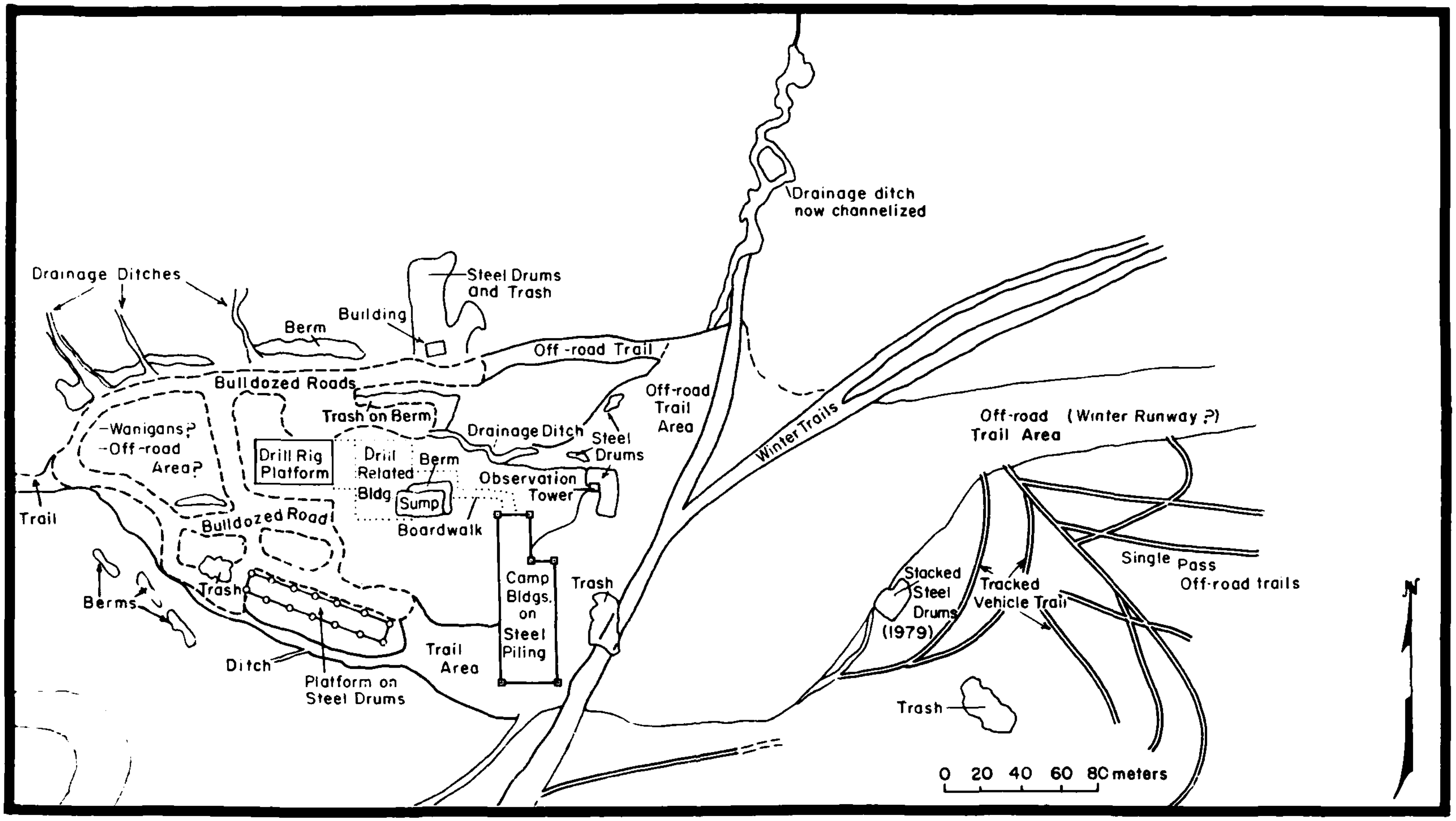


Figure 6. Locations of primary structures and roads at the East Oumalik drill site determined by observations of the site in 1978 and examining site records.

forklift. Vehicles also transported supplies and water to the camp from the airstrip and nearby stream (U.S. Navy 1951).

The drill was set on a foundation of 30.5-× 30.5-cm (12-×12-in.) timbers beneath which a refrigeration system was connected. This system consisted of 2.5-cm (1-in.) pipe cleated to the underside of each timber and through which mechanically cooled diesel oil was circulated. This system was installed to prevent thawing of the ground beneath the rig (U.S. Navy 1951).

The layout of the camp and activities on the site were unfortunately poorly documented. The drill rig, derrick and most camp buildings were removed in 1951, but items such as the rig foundation, wooden structures constructed on site, piles and solid waste were left behind. The debris remained scattered across a 3-km² area in and around the camp's location in 1978 and was used to construct a map showing the approximate locations of structures, roads, excavations and dump areas (Fig. 6). This camp appears typical of others in PET-4 that are described in more detail by Reed (1958). This camp has since been cleaned up and the debris was either removed or buried in a pit excavated on-site in 1980-1981 by NPRA clean-up crews. This burial pit is located south-southwest of the original site in previously undisturbed upland materials.

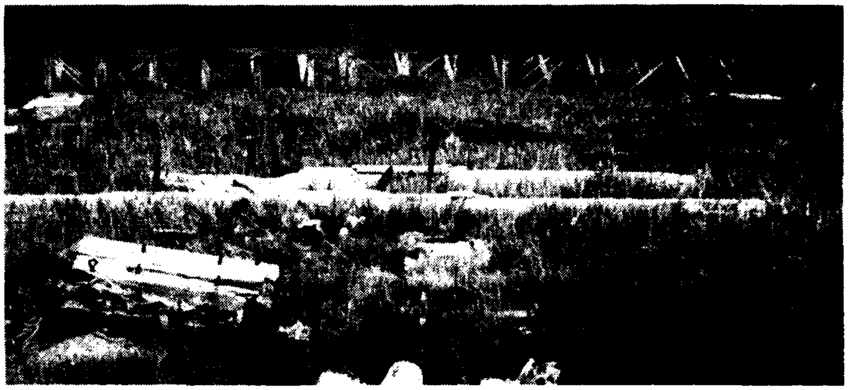
TYPES OF DISTURBANCE

The types of disturbance—camp activities and construction—can be categorized according to the first physical modification they caused. These categories are: 1) trampling and compaction of the organic mat including the living vegetation, 2) killing of vegetation, 3) removal of the vegetative mat and 4) removal of near-surface sediment with vegetative mat (Table 1). This grouping is similar to that proposed by How (1974), and by Grave (in Brown and Grave 1979). Each type of disturbance is described in more detail in Table II of Lawson et al. (1978).

The response of the site to the various activities differs according to the degree of alteration to the thermal regime of the affected area. Compaction of the surface organic material or killing of plants modifies the thermal properties of the vegetation, soil layer and possibly underlying sediments, causing a reduction in the insulating properties of the surface materials during thaw (see for example, R.J. Brown 1963, Bliss and Wein 1971, Heginbottom 1971, 1973, Linell 1973, Mackay 1970). However, the severity of trampling and compaction or the rate at which the vegetation is killed can vary, resulting in some variation in at least the initial effect of disturbance. Areas affected by removal of the vegetative mat

Table 1. Classification of disturbance by activities and their initial modification to vegetation, soils and sediment.

Type of disturbance	*Initial modification*	*Types of activities*
1	*Trampling and compaction of vegetation*	a. Off-road vehicle movements, single and multiple passes by wheeled and ski-mounted vehicles b. Snowpads (e.g. winter trails) c. Footpaths d. Temporary storage of supplies
2	Killing of original vegetation	a. Hydrocarbon spills (diesel fuel, crankcase oil) b. Boardwalk and elevated buildings c. Solid waste (e.g. steel drums, tarps, woodpiles, nondegradable waste) d. Berms (spoil piles) formed along bulldozed trails and excavations
3	Removal of vegetative mat	a. Shallow bulldozed roads b. Shallow excavations for building foundations c. Piling (local) d. Tracked vehicle movements
4	Removal of near-surface sediment with vegetative mat	a. Bulldozed roads b. Excavation of trenches, drainage ditches and sump c. Basement excavations for drill rig piling



a. Former location of timber beam foundation for drill rig; pipes with refrigerant were attached to the beams to retard thaw (disturbance category 2).

b. Tilted steel pilings that formerly supported a camp building (disturbance groups 3 and 2).

Figure 7. Lightly disturbed areas.

and upper soil horizons show the most extensive and permanent changes, in some cases leaving no trace of the initial cause of the degradation. Examples of areas affected by various types of disturbances are shown in Figures 7-10.

Areas at East Oumalik where the vegetative mat and soil were removed by the activities of categories 3 and 4 (Table 1) are now characterized by differential subsidence ranging from 3 to 5.5 m, poor drainage with some standing water, an incomplete cover of vegetation and an active layer thickness ranging from 0.8 to over 2 m. Areas in which the vegetation was simply killed but not removed by category 2 activities have 1)

Figure 8. Subsided area traversed by camp vehicles on northeast area of site (disturbance group 1).

Figure 9. Former bulldozed trail at northeast corner of former site (view northeast). Present ground surface is over 5 m lower in elevation than the original ground surface (disturbance group 4). Polygonal trough pattern covers bottom.

Figure 10. Former drainage ditch on north margin of site; thermal and hydraulic erosion developed channel over 3 m deep (disturbance group 4).

undergone a generally uniform subsidence ranging from 0.1 to 1.1 m (typically 0.3 m), 2) become reasonably dry through most of the year, 3) been completely revegetated, and 4) developed a 0.3- to 0.6-m-thick active layer.

The degree to which compaction resulting from activities in category 1 has actually modified the terrain depends upon the intensity of compaction and disruption to the uppermost organic-rich soil horizon. For example, single-pass, off-road vehicle trails have minimal thaw subsidence of 0.1 to 0.3 m with few other changes except in the composition of the vegetation, whereas multiple pass trails at East Oumalik show differential subsidence of up to 4 m, variable moisture and drainage conditions (often with standing water), a mostly complete but modified vegetation cover and active layer thicknesses of about 0.6 to 1.5 m.

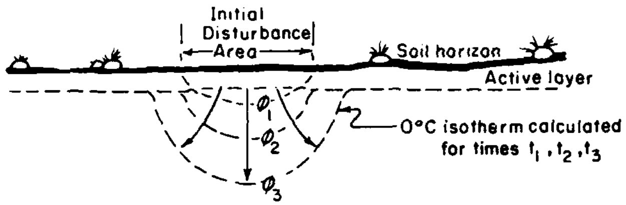
DEGRADATIONAL PROCESSES AND THE EFFECTIVE AREA OF IMPACT

The effects of camp and construction activities on the drill site were determined not only by the type of disturbance and its immediate modification of the terrain, but also by the more long-term cryogenic and sedimentologic processes initiated. These long-term processes are responsible for the extensive lateral expansion of terrain modification beyond the areas initially disturbed.

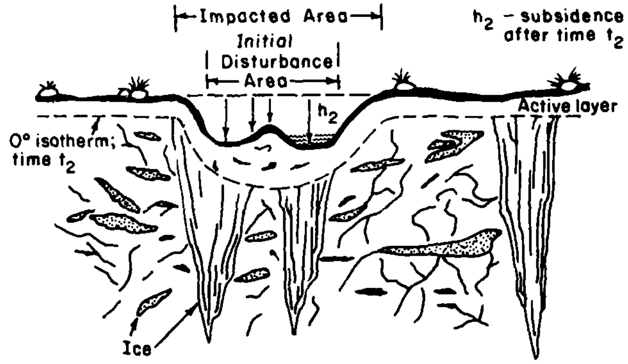
The primary reasons for this expansion are three-fold: 1) the properties of the sediments made them highly unstable upon thawing, 2) both natural relief and changes in slope and elevation due to thaw subsidence permitted runoff of meltwater and induced other degradational processes, and 3) these degradational processes perpetuated thermal disequilibrium and continued expansion of thaw into adjacent near-surface materials.

The increase in active layer thickness and deepening of the annual depth of thaw (taken as the 0°C isotherm) which result from a local terrain disturbance (Fig. 11a) are in general analogous to the development and expansion of a thaw bulb beneath lakes and rivers (Brewer 1958, Lachenbruch 1959). Ideally, the rate of expansion of the thaw bulb is a function of effective change in temperature at the ground surface and thermal properties of the sediment. Under isotropic and homogeneous conditions, the vertical and lateral expansion rate beneath a limited area of disturbance will decrease with time until it becomes stable (McRoberts 1978).

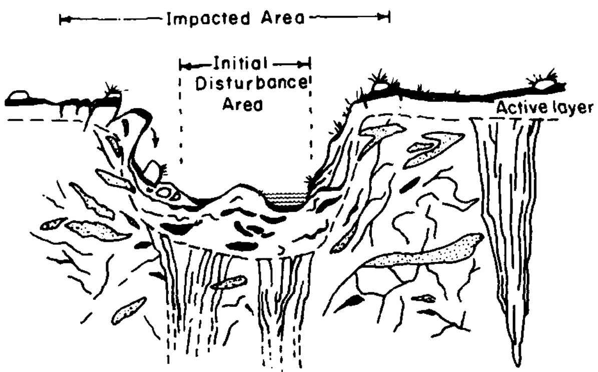
During thaw bulb expansion, however, melting of ground ice will cause subsidence of the ground surface that is approximately proportional to the volume of ice in excess of the pore space of the sediment in an unfrozen state (see



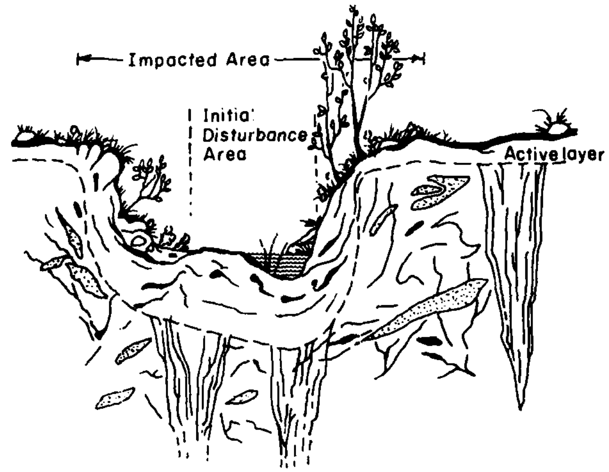
a. *Thaw bulb expansion with time (ϕ_1, ϕ_2, ϕ_3) after a thermal disturbance at the surface. Limit of thaw bulb taken as 0°C isotherm.*



b. *Differential thaw settlement and consolidation of perennially frozen ground containing ice. Area of impact is about equal to that actually disturbed.*



c. *Lateral expansion of degradation resulting from gravitational slope processes (sediment flow, slump, spall, sheet flow of meltwater) initiated as limits of thaw bulb and relief due to subsidence increase. Thaw bulb expansion is then enhanced by physical modifications. Impacted area now exceeds area of initial disturbance*



d. *Reduced activity of degradational processes and thaw bulb expansion; revegetation enhances stability. Degradational processes appear inactive across the site today, with vegetation partly covering subsided areas.*

Figure 11. Thermal and physical modifications of ice-rich permafrost terrain at East Oumalik.

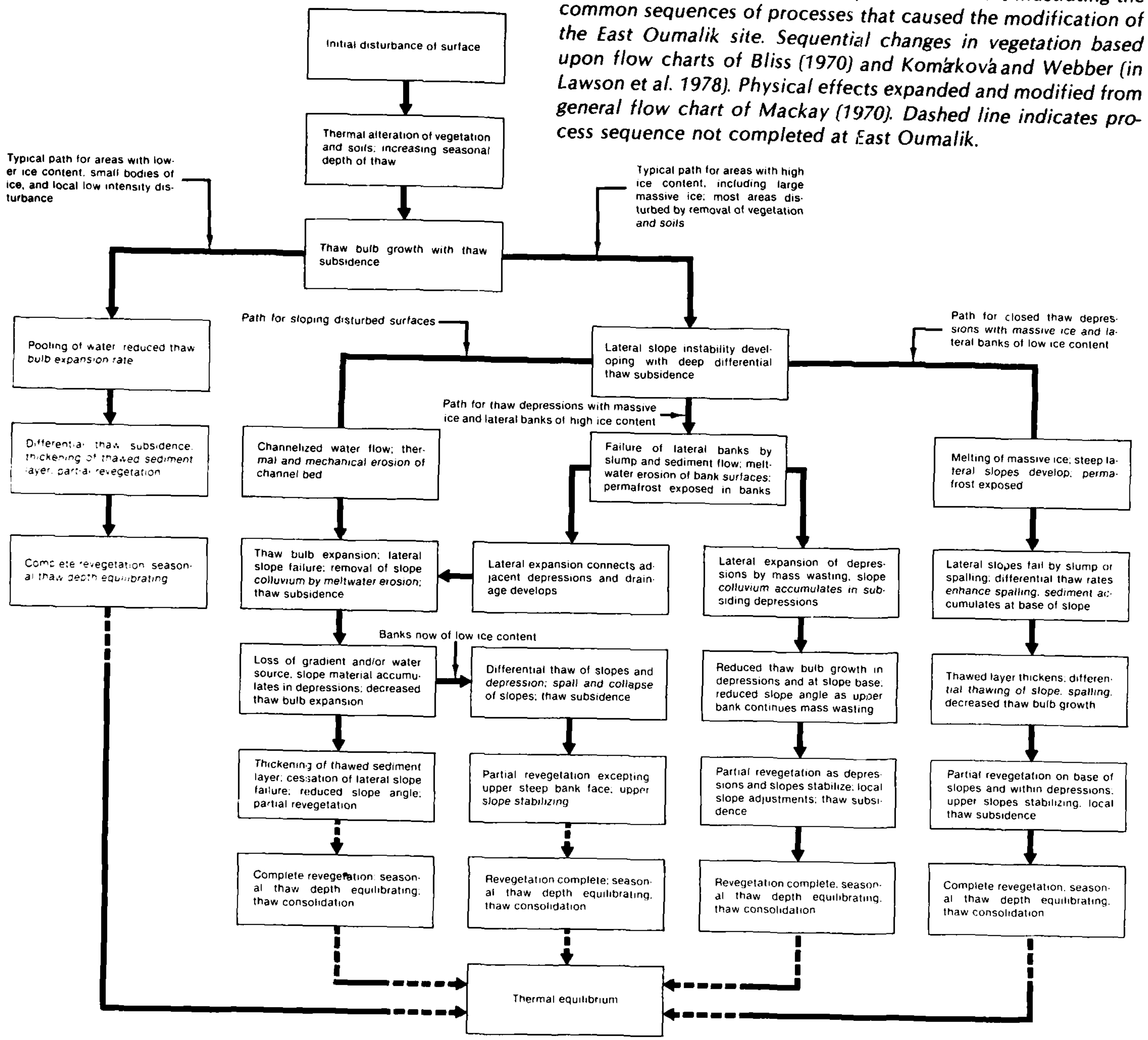


Figure 12. Schematic process-response flow chart illustrating the common sequences of processes that caused the modification of the East Oumalik site. Sequential changes in vegetation based upon flow charts of Bliss (1970) and Komárková and Webber (in Lawson et al. 1978). Physical effects expanded and modified from general flow chart of Mackay (1970). Dashed line indicates process sequence not completed at East Oumalik.

for example, Morgenstern and Nixon 1971, Nixon and McRoberts 1973, Crory 1973, Nixon and Ladanyi 1978). If the meltwater flows away from the subsiding area, melting of the ground ice effectively increases the depth to which thaw occurs because insufficient sediment is released to form an insulating cover.

Melting of the ice during thaw consolidation may also generate excess pore pressures that reduce the strength of the thawed material (McRoberts and Morgenstern 1975, McRoberts et al. 1978). Larger ice bodies (layers, large lenses and massive ice) can generate sufficient excess pore fluids to produce an unstable condition in overlying fine-grained sediment (Nixon 1973). These materials will fail if excess pore pressures become equal to the overburden weight of the thawed sediments. Remolding in response to movement can cause these materials to liquefy rapidly and flow.

If failure conditions are met repetitively and thawed sediments undergo transport by mass movement or are removed by meltwater during thaw subsidence, neither a stable physical condition nor a thermal equilibrium will develop. Thus, the area of sediments affected by degradational processes will continue to expand beyond limits defined by simple thaw bulb formation beneath a disturbance.

This "worst case" scenario represents the typical response to disturbance at East Oumalik (Fig. 12). As thaw began, melting of excess ice quickly led to subsidence (Fig. 11b). Subsidence was substantial because of the high volume of ice in undisturbed upland sediments. Samples contained 40 to nearly 100% ice by volume (mean = 85%). Large ice lenses and ice wedges are common and compose an estimated 60% by volume of the upper 10 m of perennially frozen upland materials. The ice wedges range from 5 to 10 m in

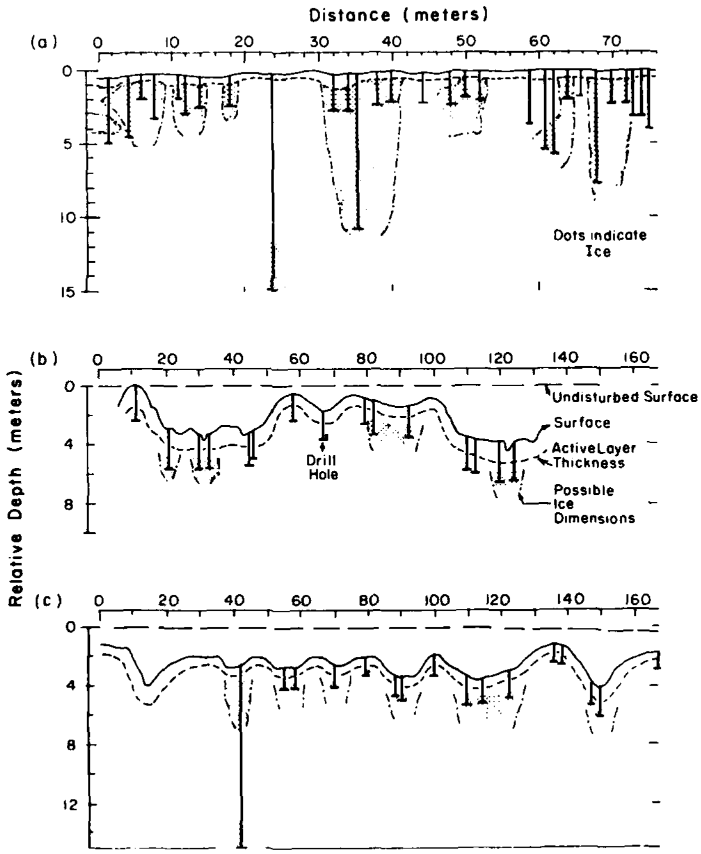


Figure 13. Stratigraphic cross sections of (a) undisturbed and (b, c) disturbed upland sediments at East Oumalik. Uppermost dashed line on (b) and (c) represents profile of the ground surface prior to disturbance. Locations of ice were defined by drilling at indicated locations and in (a) by augering to a 1.5-m depth every 2 m along the transect.

width at the top and extend 7 to 14 m deep (Fig. 13). There appear to be two sets of ice-wedge polygons, only one of which has surficial expression as a polygonal trough pattern.

The more rapidly subsiding areas were lowered significantly below the elevation of the undisturbed surface. The lateral slopes of these depressions were stable intially because of the permafrost within them, but this increase in relief then became a factor in the lateral expansion of degradation.

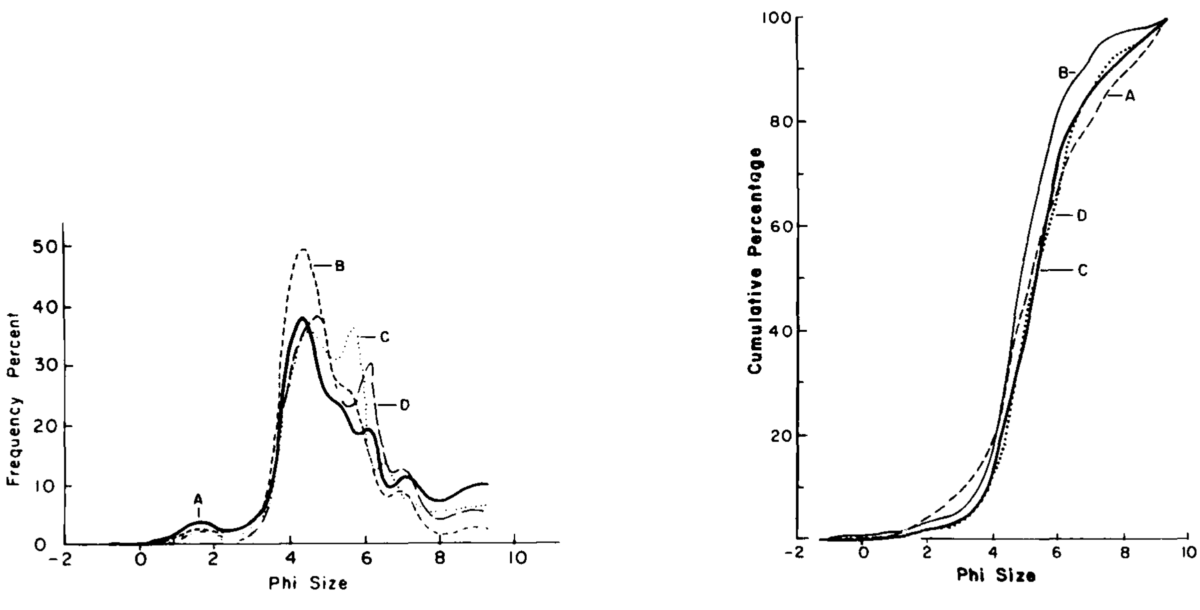
The slopes bounding the depressions became highly susceptible to failure as thawing laterally expanded because of the physical properties of the sediments (particularly ice content). Undisturbed perennially frozen sediments of the upland are rather homogeneous and composed of moderately sorted, medium silt (Fig. 14). Most samples had a bimodal size distribution with primary modal sizes of coarse and fine silt.

The condition of the silt after it thaws is indicated by its in-situ water content, degree of saturation and liquidity index. Samples of undisturbed silt of the upper 15 m of upland had water contents ranging from 45 to 500% of dry weight (typically 70 to 160%) and most were oversaturated. Similarly, the natural water content of the thawed silt was usually greater than its liquid limit. The liquidity index I_l of the silt, as defined by the ratio:

$$I_l = \frac{(w - P_w)}{(L_w - P_w)} \qquad (1)$$

(where w is the natural water content, P_w the plastic limit and L_w the liquid limit) was usually greater than 1. If $I_l > 1$, remolding will rapidly liquefy the material (Terzaghi and Peck 1967). Failure of such thawed materials on a sloping permafrost surface will take place at very low slope angles (<15°) (Morgenstern and Nixon 1971).

Comparison of the in-situ water content and liquidity index clearly demonstrates the inherent instability of the silt after thawing (Fig. 15). Based upon these data and comparison to data of Nixon and Hanna (1979) and others, it is highly probable that the thawed silt had little or no shear strength. Melting of the prevalent massive ground ice undoubtedly was also responsible for local increases in pore pressure and loss of strength. As a result of the silt's instability after thawing, gravitationally induced slope processes, including slump, debris flow and liquefied flow, became active (Fig. 11c). The oversaturated silt also offered little resistance to hydraulic erosion from meltwater flowing off the thawing slopes and within thaw depressions. Initial slope failures may have resulted from slumping along the interface between thawed sediment and frozen sediment (or ice) after excess pore



a. Frequency curves.

b. Cumulative curves.

Figure 14. Representative frequency curves (a) and cumulative curves (b) of grain size distribution of samples from upland silt (<10-m depth) at East Oumalik. Frequency curves computed by numerical differentiation.

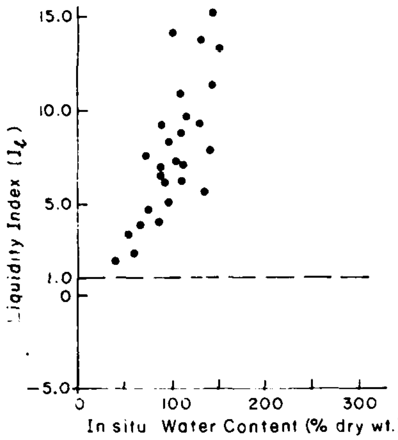


Figure 15. Water content of frozen undisturbed silts compared to their liquidity index.

pressures had reduced the shear resistance here to less than the gravitational force (Terzaghi 1950, Morgenstern and Nixon 1971). Lateral expansion of thaw depressions by slope failures eventually caused coalescence of depressions that had initially developed beneath unrelated disturbances.

Meltwater flowing from the thawing sediment and from surface runoff created channels in subsiding areas beneath bulldozed roads, drainage ditches, polygon troughs and other interconnected thaw settlement features. Thinly laminated deposits in some of the former channels indicate that meltwater flow eroded and redistributed sediments that had been transported into the depressions by the mass wasting processes. The coalescence of depressions forming beneath adjacent areas of disturbance also resulted in gully formation wherever sufficient gradients existed. Closed thaw depressions, some with channelized flow into them, filled with meltwater.

When subsidence rates were much greater than rates of lateral expansion, steep, near vertical slopes developed (Fig. 11c). Such slopes also developed when bank sediments of low ice content were adjacent to subsiding areas of high ice content. These slopes did not fail immediately because the frozen sediments outside the thaw bulb provided strength and stability. Differential rates of thawing eventually induced tensional fracturing of the sediments and vegetative mat at the top of the slope. As these materials became oversteepened, they underwent spalling and collapsed into the depressions. Banks of high ice content also failed by slump and flow. Colluvial deposition in depressions retarded this thawing and enhanced the stability of the lower part of the slope. Differential thawing rates led to further degradation of the upper slope materials at some locations, while at others, thawing was reduced sufficiently to stop spalling. At these latter locations, vegetated tundra blocks remain perched at the top of the slope today (Fig. 11d). Similar blocks are also buried in sediments of thaw depressions.

Several conditions developed to retard thaw bulb expansion and stabilize slopes (Fig. 11d). These conditions included 1) thickening of sediments in the thaw bulb due to thaw or deposition, including that at the base of depressional slopes, 2) deposition and/or differential thaw along the longitudinal axis of gullies to reduce or eliminate the drainage gradient, 3) reduced meltwater production, perhaps as massive ice melted completely or as rates of thaw slowed due to sedimentation, and 4) revegetation of the bottoms and lower slopes of depressions. Snow banks that form within depressions and gullies also slowed spring thaw and locally reduced the length of the melt season. Vegetation grows on much of the disturbed site today, with bare areas limited to the bottoms of the largest depressions, the upper parts of steep near-vertical slopes, and the locations where solid debris was removed during clean-up of the site in 1980. Considering the types and interrelationships of the degradational processes and the condition of the site from 1978 to 1981, the degradational processes were probably most active for 10 to 15 years following disturbance with activity diminishing since then to its present level.

Areas that were not intensely disturbed (e.g. single off-road vehicle passes, areas beneath buildings or next to piles) underwent thaw subsidence, but were generally unaffected by other degradational processes. Thaw subsidence developed smaller depressions without well-defined slopes so that erosional processes were less active. Deeper subsidence in these areas resulted from the partial melting of ice wedges.

AREAL EFFECTS OF DISTURBANCE

The degradational processes resulting from disturbance have caused a substantial reshaping or altering of the upland topography, drainage, near-surface sediments, vegetation (Komárková and Webber 1980) and soils.* These changes

*K R Everett, Ohio State University, pers. comm., 1981

have apparently led in turn to a permanent change in the near-surface thermal regime of the site.

Topography

Surficial changes in the site are clearly evident on aerial photographs taken in 1978 (Fig. 16). The relatively featureless upland surface on the 1948 aerial photograph (Fig. 4) is now covered by hummocks and depressions with a distribution controlled by the former location of the camp and vehicle trails. Depressions, up to 5.5 m in depth, are mostly irregular in shape, size and distribution (Fig. 17). The deeper depressions are, however, generally interconnected with drainage ditches or gullies located on the valley slopes. Relief across the site exceeds 8 m, whereas relief was probably less than 2 m prior to occupation. A polygonal pattern of troughs formed by the melt-out of ice wedges is apparent in the less intensely disturbed areas of the site (Fig. 16). It is also present in the bottoms of some of the larger and deeper depressions (Fig. 9).

Groundwater, surface water and drainage

Observations and measurements at different times throughout the year in undisturbed areas of the upland indicate that the water content of the active layer varies with the microtopography of the upland but shows relatively little point-to-point variation. During winter, snow accumulation is low on the upland (less than 40 cm) due to lateral wind transport of the snow to other areas of higher relief. The snowpack melts rapidly in spring and is normally completely dissipated by mid-June. Runoff from snowmelt moves off the uplands in small rills (channels of 2- to 10-cm depth) between the tussocks on valley slopes ("water tracks") and in somewhat larger (10- to 20-cm-deep) polygonal troughs above ice wedges. Subsurface flow occurs on top of the mineral soil at the base of the surface organic layer and at the interface of the unfrozen and frozen horizon in the active layer. By summer's end, shallow groundwater from melting ground ice flows through the active layer on the upper surface of the permafrost. Standing water is generally restricted to the small troughs above ice wedges and to the deeper depressions between tussocks.

As a consequence of the topographic changes the distribution and movement of both surface water and shallow groundwater flow above permafrost have been substantially altered. Low areas in the disturbed parts of the upland are now much wetter year-round. Across the site, water remains ponded in depressions between drier hummocks and in trenches located above partly melted ice wedges; some of these have remained water-filled (up to 1.0 m deep) from July 1978 to September 1981. Individual depressions are often closed basins with water perched in them above impermeable permafrost and with individual basins separated by dry hummocks in which the permafrost is closer to the surface. Most former drainage ditches and interconnected depressions have water flowing in them during melting of the snowpack, but they contain only standing water in isolated depressions during the remainder of the year. Snow that drifts into the various subsidence features in winter may remain in the deeper depressions until late July, thus reducing the length of the thaw season and inhibiting water flow at these locations. These snowbanks provide local sources of meltwater later into the summer than elsewhere on the upland.

Sediment properties and near-surface stratigraphy

Properties of sediment beneath disturbed areas have been modified so that they now generally differ from undisturbed active layer and perennially frozen materials. Thawing has eliminated the massive and segregated ice of the uppermost permafrost, while thaw consolidation has increased the particle packing and decreased the pore spaces and voids in the disturbed sediment (Fig. 18). As expected, no significant change in the grain size of the surficial sediments was found. Moisture contents have been reduced and usually range from 18 to 40% of dry weight in hummocks and up to 120% of dry weight in wet depressions. Ice volumes of seasonally frozen sediments show similar variations and rarely exceed 50%. Bulk density in these samples ranges from 1.6 to 1.9 g/cm^3, an increase of about 30%. Porosity shows a comparable decrease in value. The degree of saturation of disturbed sediments in the frozen or unfrozen state is consistently near 1.0 (saturated condition). The moisture content, ice volume and porosity of disturbed sediments are less than in the frozen active layer and perennially frozen sediment of the undisturbed upland. Density is also significantly higher.

Disturbed sediments also bear several new characteristics that were developed during degradation. In undisturbed areas, a peat horizon

Figure 16. Mosaic of aerial photographs of the East Oumalik drill site in 1978. Areas marked 1, 2, 3 and 4 refer, respectively, to parts initially affected mainly by disturbances of groups 1, 2, 3 or 4. Two large gullies, former drainage ditches, are located on the valley slope of the site's northern margin. The black line locates the approximate area of activities during occupation in 1950 (photographed by R. Haugen of CRREL). A–A' and B–B' locate end points of cross sections shown in Figure 17.

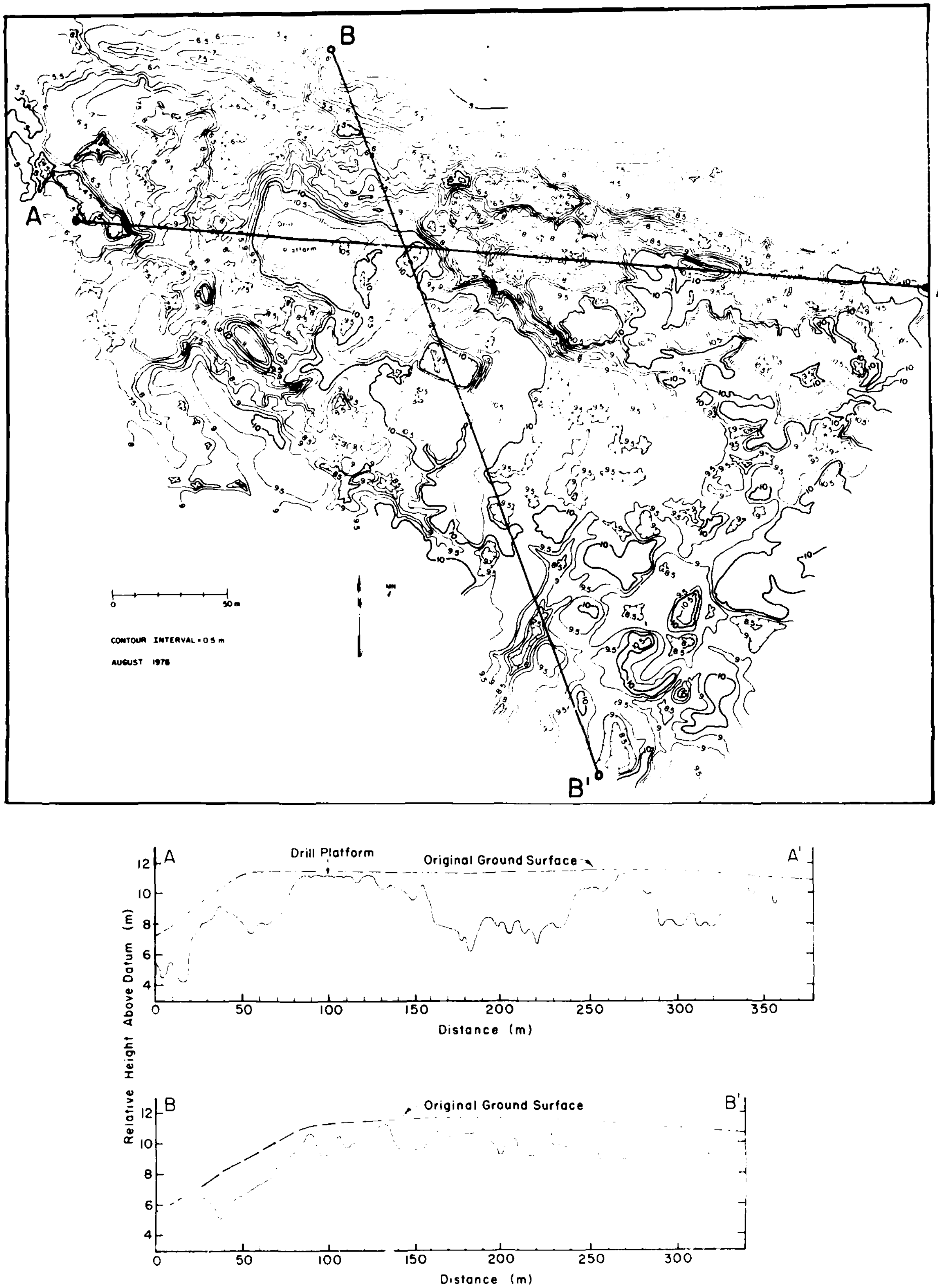


Figure 17. Topographic map and cross sections of the East Oumalik drill site in 1978. Locations of cross sections A-A' and B-B' are also shown in Figure 16.

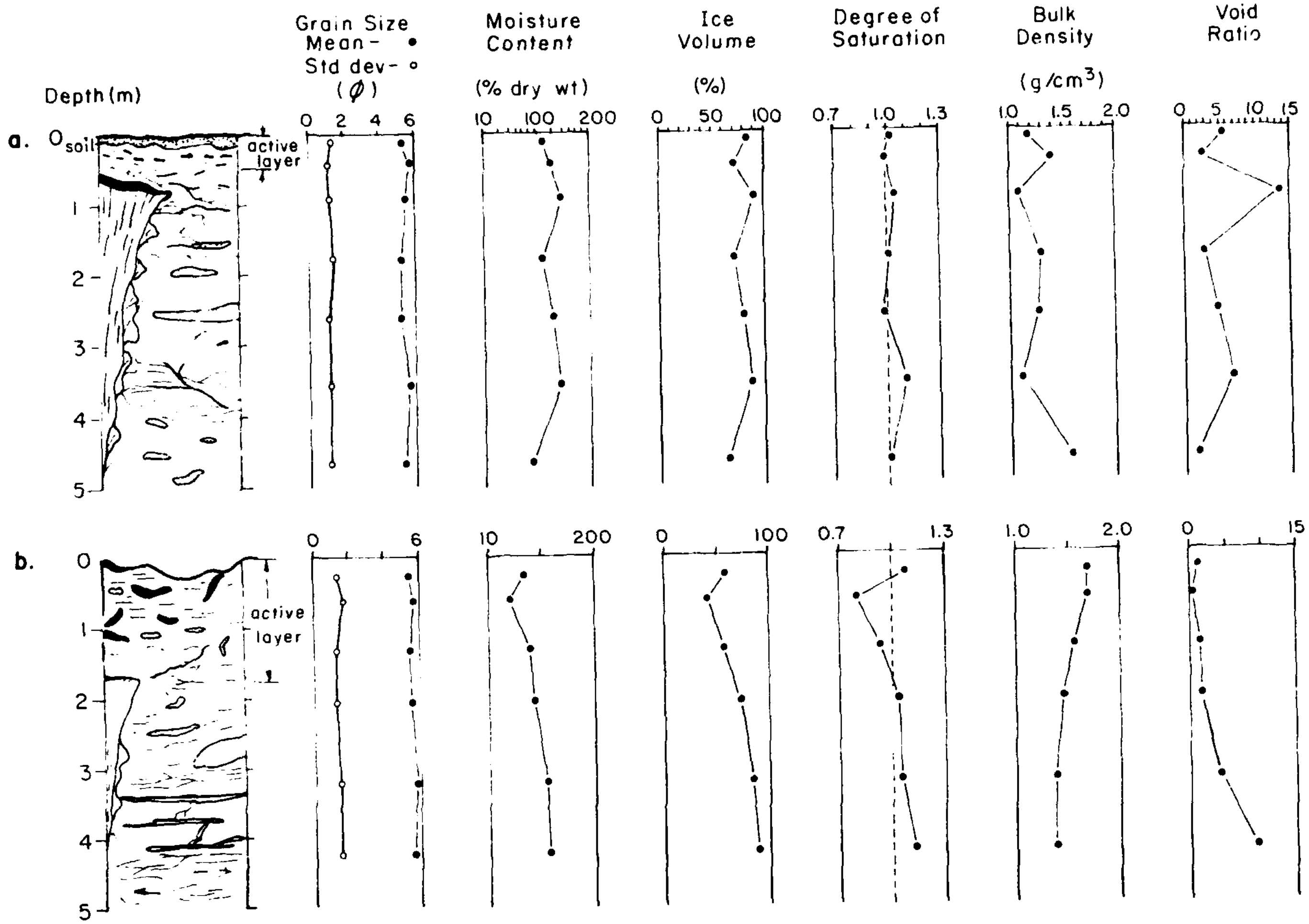


Figure 18. Comparison of properties of typical stratigraphic sections of (a) undisturbed upland and (b) thaw depression in disturbed upland. Data represent samples of sediments (not massive ice) shown in cross sections.

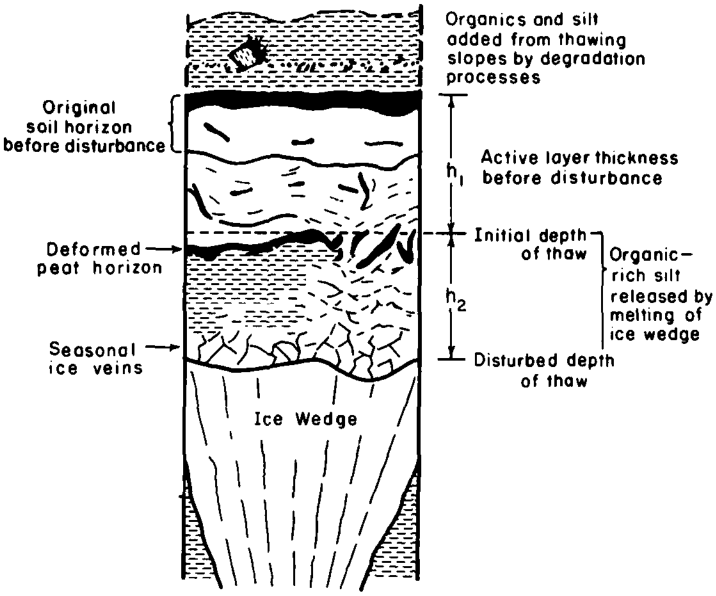


Figure 19. Stratigraphic profile observed above partly melted ice wedge at East Oumalik. Peat horizon was located on top surface of ice wedge before melting began. Organic-rich silt of thickness h_2 *was melted from the wedge and deposited in situ. Measurements of* h_1 *typically range from 0.35 to 0.60 m and of* h_2 *from 0.05 to 0.35 m.*

commonly lies on the top surface of ice wedges. As these ice wedges melt because of disturbance-induced thawing, they release the sediment and organics that are contained in the wedge ice. This material is immediately deposited in situ between the peat and the remaining wedge ice. The thickness of this layer (h_2 in Fig. 19) is thus determined by the material content of the ice wedge—typically 0.5 to 5% by volume (mean 2.2% of 20 samples). This zone of melted-out sediment was up to 0.35 m thick in the deepest depressions on the drill site. In each of the 10 sequences above partly melted ice wedges examined, I found no indication of a contribution of sediment from the lateral slopes.

This peat-sediment-wedge ice sequence is therefore a product of the disturbance-induced thaw at East Oumalik. This stratigraphic sequence may also be applicable elsewhere for defining areas where thaw depths have been increased in the geologically recent past in response to climatic or other natural modifications of the thermal regime (see Brown 1967, Fig. 5, for a similar sequence above a buried ice wedge).

Soil horizons and sedimentary stratifications were folded and reoriented at several locations as excess ice melted and thawed sediment consolidated. The mass movement of slope material onto oversaturated sediments in depressions also occasionally caused some to become convoluted.

Slope processes also modified the stratigraphic profile in depressional areas by 1) burying soils beneath slope-derived material, 2) transporting and depositing intact blocks of the tundra vegetation and soil, and 3) producing stratified sediments due to interspersed, repetitive periods of meltwater and sediment flow deposition.

Surficial processes

Most of the site no longer appears to be degrading physically; however, some degradational processes remain visibly active along the southwestern margin of the disturbed area and locally within the site. The most important include the following:

1. *Thermal degradation and ground subsidence.* These processes are active on the southwestern margin where they are expanding thermokarst into apparently undisturbed parts of the upland (Fig. 16). An ice wedge exposed in a collapsing bank of

a thermokarst pond in 1978 subsequently melted by 1980 and became a 2-m-deep depression filled with water year-round.

2. *Spall and collapse.* Spalling also appears to be active in modifying steep slopes that bound at least two of the deeper thaw depressions on the former site. Fresh blocks of the vegetative mat and soil, typical of those released by spalling, occur at the base of these slopes.
3. *Mechanical and thermal erosion.* Runoff in gullies remains important during peak flow periods, with some transport of sediment from the site into the adjacent valleys. The sediment appears to be derived mainly from areas of bare ground and from colluvial material previously deposited by freeze-thaw and other slope processes.
4. *Freeze-thaw.* Sediments exposed across the site are susceptible to freeze-thaw processes, which cause cracking and loosening of aggregates of sediments in slope faces. The sediments move downslope by falling and rolling under the force of gravity.
5. *Eolian activity.* Unvegetated, dry sediments exposed at the tops of slopes bounding depressions and hummocks are eroded and blown about on windy days.

Depth of thaw

The seasonal depth of thaw beneath the drill site appears to be permanently altered. Active layer thicknesses measured by probing with a steel rod in July 1978, September 1979 and September 1981 were thicker and had a wider range in value in disturbed areas than in the undisturbed upland. In July 1978, for example, this difference in active layer thicknesses ranged from 10 to 90 cm between disturbed and undisturbed areas.

Within the disturbed upland, active layer thickness varies with the present topography and drainage conditions (Fig. 20). Largest active layer thicknesses occur in depressions developed by removal of the vegetative mat and soil by bulldozing, or in former gullies developed by thermal and hydraulic erosion. In less intensely disturbed areas, such as beneath buildings and off-road sites, thaw depths in depressions are generally lower by 30 cm or more.

The active layer thickness of disturbed areas may now represent thermal conditions determined by the present physical conditions of the site, suggesting that the depth of thaw may be approaching equilibrium. Comparison of thaw depths of disturbed areas in July 1978 to those from similar undisturbed areas of the upland and adjacent stream valleys (Fig. 21) suggests that factors such as drainage, presence of standing water, topography and type of vegetation may be determining the disturbed area's present seasonal thaw depth.

A more detailed analysis is required, however, to determine if the new physical and thermal conditions are in equilibrium or if the seasonal depth of thaw is still changing. The ice wedges which were exposed in 1978 and 1980 near the southwestern margin of the site are clearly indicative of continuing thermal modifications in these previously undisturbed areas. Thermal modification is also probably continuing to a limited degree around the larger thaw depressions and slopes within the original site. For the remainder of the site, which appears physically inactive, it could not be determined by this study if thermal changes are continuing.

Unfortunately, there are few studies which have examined the length of time necessary to achieve thermal equilibrium at a disturbed site. Most of these studies have examined a site's thermal stability for only a short time (10 years or less) after the initial disturbance. Some sites have apparently reached thermal equilibrium in this time frame (e.g. Mackay 1977), while others continue to show thermal modifications (e.g. French 1975, Viereck and Dyrness 1979, Viereck 1982). None of the studies provides sufficient data to allow correlations between sites with different types of disturbances or physical conditions. Studies by Linell (1973) and Viereck (1982) however, indicate that the development of a deep organic layer is probably very important in stabilizing active layer depth. Because of the complex interaction of physical parameters that affect the thermal regime of a disturbed site, there are undoubtedly substantial differences in the length of time over which thermal as well as physical changes will take place.

An additional factor affecting both thermal and physical response (which could not be evaluated for this study) is thermal disequilibrium between the present climate and the permafrost of the region. Other upland areas in this region are now developing thermokarst in response to natural processes. If a disequilibrium condition exists, even a slight disturbance could cause degradation to spread progressively into adjacent undisturbed areas and the intensity of disturbance would not necessarily be related to the impact resulting from disturbance. The present

Figure 20. Isopach lines of active layer thickness on 26 July 1978, drawn on the 1978 aerial photography (100 measurements). Undisturbed upland thicknesses range from 23 to 32 cm with larger thicknesses in disturbed areas.

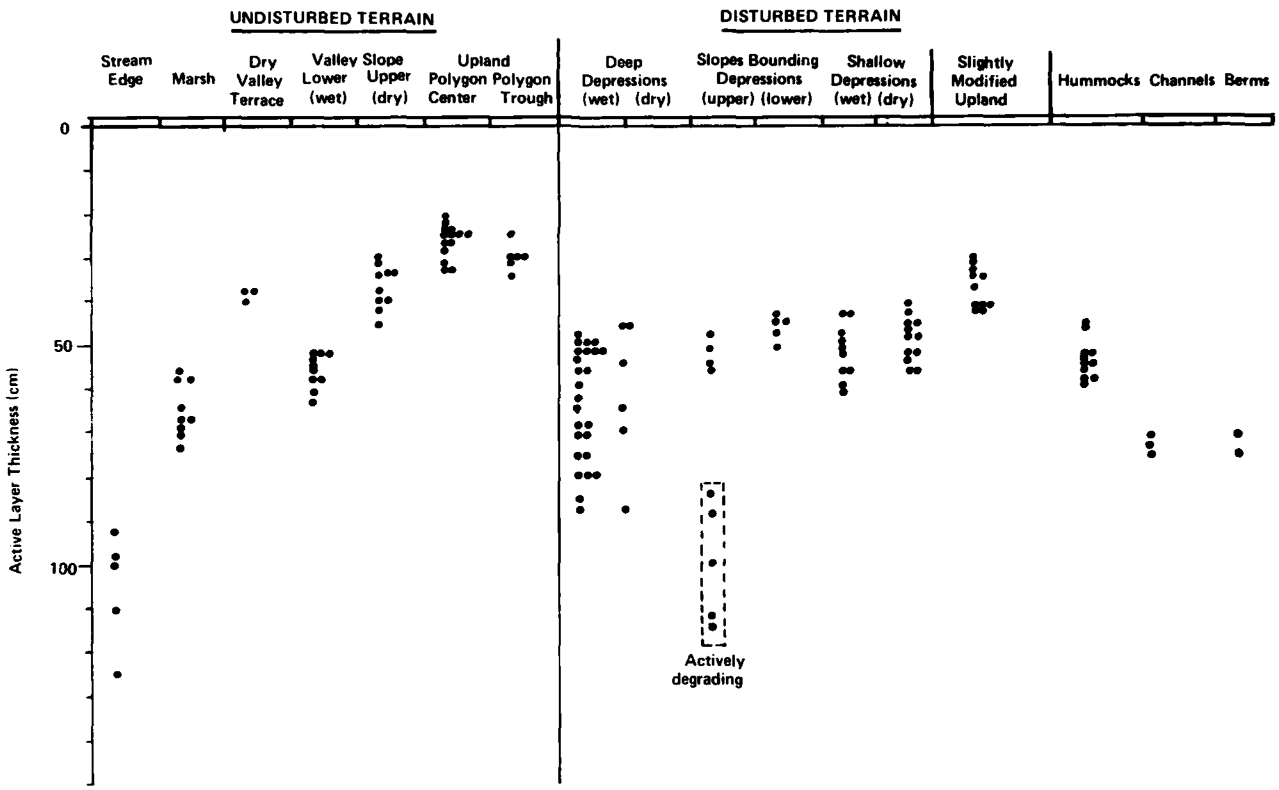


Figure 21. Comparison of active layer thickness in July 1978 in disturbed and undisturbed parts of upland and surrounding stream valleys.

activity of degradational processes near the site's southwestern margin may partly represent such a response. Further analysis is required before the thermal stability or instability of the East Oumalik site is understood.

COMPARISON TO FISH CREEK

Another old drill site in the NPRA, Fish Creek, 175 km northeast of East Oumalik (Fig. 1), was examined in 1977 and 1978 to define the physical and biological modifications that resulted from drilling activities that took place from March through October 1949 (Lawson et al. 1978). I later examined the properties of near-surface materials in 1979 and 1980 for this study, by coring 45 holes ranging in depth from 2 to 15 m and analyzing their properties using the same techniques as described earlier for samples from East Oumalik.

The camp and exploratory well at Fish Creek were established upon a moderately drained upland surface next to two naturally drained lake basins and a stream valley (Fig. 22). The uppermost 5 to 10 m of this upland is composed of moderately well-sorted, fine sand (Fig. 23) of eolian origin (Carter 1981).

Drill holes encountered very few ice lenses in undisturbed upland sand with visible ice restricted mainly to pore ice (Fig. 24). Ice wedges range from 1.1 to 2.4 m in width at the top and extend about 1.5 to 3.2 m below the surface. At this site, ice lenses occur more frequently in the sand and silty sand of the lake basins, but ice wedges here are comparable in size to those of the intervening uplands. The upland surface is relatively flat with tussock tundra vegetation covering undisturbed areas. Maximum relief between the upland surface and bottom of the largest lake basin is about 5 m. Construction activities in 1949 were mostly confined to the upland areas, but vehicle movements, drainage ditches and trash dumps disturbed parts of the drained lake basins (Fig. 22).

Although both sites experienced occupation for about the same length of time during the

Figure 22. Aerial photograph of the Fish Creek drill site in 1977. Camp activities were mostly confined to an upland area composed of eolian sand. Drained lake basins east and south of the main camp and the stream valley to the west were also locally disturbed by bulldozing, vehicle movements and trash dumping. The concrete drill pad 1), buildings on pilings 2), bulldozed roads 3), off-road trails 4), multiple pass off-road trails 5), bulldozed drainage ditches 6) and a steel drum pile 7) are indicated.

same seasons and were disturbed by nearly identical activities, the modification resulting from disturbance of the Fish Creek site is much less extensive than that at East Oumalik (Lawson and Brown 1979).

As a simple comparison of the physical effects of disturbances on the terrain of each site, I have computed a severity index (S_i) of disturbance as a ratio of the final area of impact (A_{fd}) to the initial area of disturbance (A_{id}):

$$S_i = A_{fd}/A_{id} \tag{2}$$

The disturbed area is defined as an area initially affected by some disturbance (e.g. the area of tracks of a wheeled vehicle). The impacted area

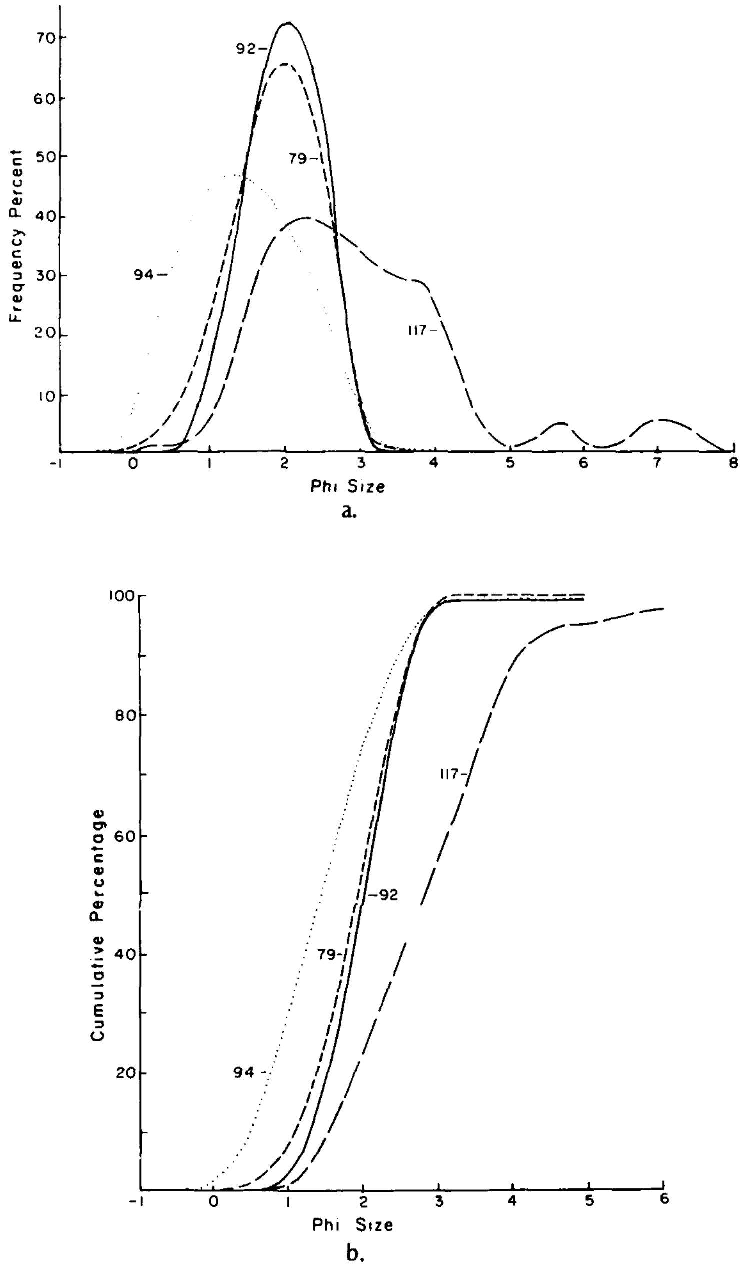


Figure 23. Representative frequency curves (a) and cumulative curves (b) of grain size distribution in samples of eolian sand at Fish Creek. Frequency curves computed by numerical differentiation.

is an area that is physically modified in response to the initial disturbance.

Thus for $S_I = 1.0$, the impacted area equals the area initially disturbed. For $S_I > 1.0$, the impact of disturbance has spread beyond the area physically disturbed. Values of $S_I < 1.0$ indicate that the effect of disturbance was not permanent and thus some recovery occurred to return the area to its previous condition.

In Table 2, values for S_I at Fish Creek and East Oumalik are compared for the four general types of disturbances. Typical depths of depressions are also listed. S_I values measured at East Oumalik (0.9 to 2.6) were generally much larger

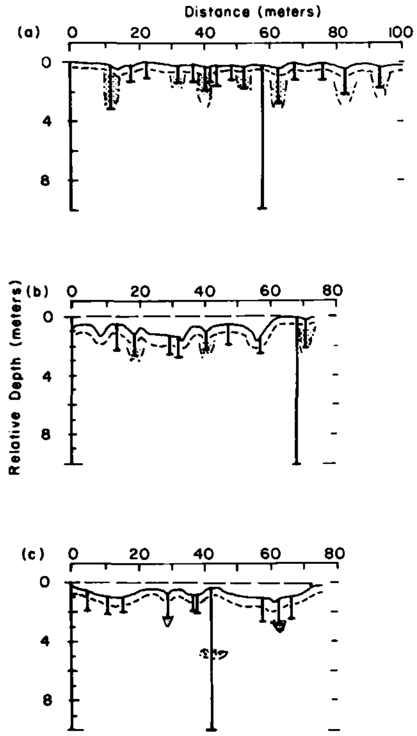


Figure 24. Stratigraphic cross sections of undisturbed (a) and disturbed (b,c) areas at Fish Creek. Presence of ground ice was defined by drilling at the locations identified on the cross sections. Uppermost dashed line in (b) and (c) represents profile of surface prior to disturbance. Other symbols defined on Figure 13. Location shown in Figure 22.

than those at Fish Creek (0.9 to 1.2). At both sites, removal of vegetation and soil had the most severe impacts. The areal extent of impact usually covers or extends beyond the boundaries of the original disturbance on the East Oumalik site, whereas it is most often limited to within the individual areas actually disturbed at Fish Creek. Similarly, the depth of depressions and also the increase in relief are much larger at East Oumalik than Fish Creek.

Three factors appear to be the most important influences on the physical modifications of the two sites: 1) spatial variability in ice volume, which directly affects the mode of degradation, 2) physical properties of the sediments, which affect their susceptibility to failure once thaw begins and 3) the local and regional slope, which affects moisture conditions, drainage and thus degradational processes.

The importance of material properties is shown by comparing the grain size, water content, dry density, void ratio and other engineering properties of samples of disturbed and undisturbed sediments of Fish Creek and East Oumalik (Table 3). These data indicate that the sediments at East Oumalik were generally unstable at thaw. In contrast, the sand at Fish Creek clearly had significant frictional resistance to shear. Water contents of the sand remain well below the liquid limits and they are generally unsaturated. Similarly, the granularity and relatively high porosity of the material suggest that pore pressures will not significantly increase during thawing.

Volumetrically, ice composed 35% more of the near-surface sediments (upper 5 m) at East

Table 2. General comparison of physical modifications to terrain at East Oumalik (EO) and Fish Creek (FC) drill sites due to disturbances listed by groups (Table 1). S_i represents areal effects and is defined in the text.

Initial disturbance	*Site*	*S_i (Severity index)*	*Depth of depressions (m)*
Group 1	EO	1.1 to 1.43	0.7 to 4.2
	FC	1.0	0.1 to 0.7
Group 2	EO	0.9 to 1.1	0.1 to 1.1
	FC	0.9 to 1.0	Up to 0.2
Group 3	EO	1.7 to 2.6	3.1 to 5.5
	FC	1.0 to 1.2	0.2 to 1.5
Group 4	EO	1.25 to 2.5	3.0 to 5.0
	FC	1.0 to 1.2	0.4 to 2.0

Table 3. Selected properties of near-surface sediment from undisturbed and disturbed locations at the East Oumalik and Fish Creek drill sites.

	East Oumalik upland		*Fish Creek upland*	
	Undisturbed	*Disturbed*	*Undisturbed*	*Disturbed*
Grain-size (ϕ), mean (m), std. dev. (δ)	m = 5.50 δ = 1.2	m = 5.50 δ = 1.2	m = 2.75 δ = 0.7	m = 2.75 δ = 0.7
Moisture content (% dry wt)	80 to 250	40 to 120	19 to 71 (sporadically to 120%)	22 to 28
Ice volume (%) (excludes ice wedges)	60 to 100 (m = 85)	40 to 65	23 to 68 (m = 47)	33 to 42
Degree of saturation (frozen)	0.95 to 1.2 (m = 1.05)	0.8 to 1.1	0.6 to 1.05 (m = 0.96)	0.6 to 1.0
Bulk density (g/cm^3)	0.9 to 1.6 (m = 1.2)	1.6 to 1.8 (m = 1.65)	1.5 to 2.2 (m = 2.0)	1.8 to 2.1 (m = 2.0)
Dry density (g/cm^3)	0.3 to 1.1	0.8 to 1.2	1.4 to 1.8	1.5 to 1.8
Void ratio	3 to 14	0.5 to 2.8	0.4 to 1.61	0.4 to 0.78
Liquidity index	1.6 to >15	0.9 to 1.2	-1 to 0.5	-1 to 0.3

Figure 25. Aerial photograph of area around concrete drill pad at Fish Creek site. Melting of ice wedges by surficial disturbances formed a polygonal pattern of thaw depressions. View west.

Oumalik than at Fish Creek. Also, massive ground ice composed only an estimated 20 to 25% of the upper 5 m of the Fish Creek materials, whereas it composed greater than 65% at East Oumalik. This difference results from the smaller size of ice wedges and absence of ice lenses and layers at Fish Creek (Fig. 13, 24).

The distribution and size of massive ground ice limited the depth of thaw subsidence and altered expansion of degradation at Fish Creek. The low volume of ground ice resulted in a more rapid buildup of an insulating layer of thawed sediment. Maximum subsidence values are approximately equal to or less than the largest depths of ice wedges. Because of the low relief, drainage of the central part of the site was also limited and meltwater apparently ponded in most thaw depressions. Even in areas modified by removal of the vegetative mat and soil at Fish Creek, depressions are limited in size and extent. Wedge ice was generally not encountered in drilling beneath these areas in 1979 and 1980. Wedge ice remains beneath such areas at East Oumalik, however, and dimensions of depressions are several times larger.

The fact that thaw depressions at Fish Creek form a polygonal pattern determined by the former location of ice wedges (Fig. 25) is indicative of a much less active role by gravitational slope processes in physically modifying the Fish Creek site. Present relief in disturbed areas suggests that thaw depressions did not develop marginal slopes exceeding 1 m in height and probably most were 0.5 m or less.

This increase in relief during thaw subsidence is insufficient to generate gravitational processes of the type and extent that occurred at the East Oumalik site. Lateral movement of thawed sand into subsiding areas at Fish Creek was therefore limited probably to creep (especially where the vegetation provided additional resistance to movement), small slumps, and possibly granular flow of dried sand. It basically resulted in a reduction in the angle of side slopes of thaw depressions, drainage ditches and bulldozed trails to near the natural angle of repose of the sand. Similarly, thermal and hydraulic erosion at Fish Creek were active only within drainage ditches and bulldozed trails located on the slopes of the stream valley or drained lake basins.

Subsidence of the ground surface resulting from thawing and consolidation of the sand was minimal at Fish Creek and is now reflected in small differences between the properties of undisturbed seasonally frozen sediment and disturbed perennially frozen sediment (Table 3). Of particular importance, ice volume decreased from a range of 40 to 65% in undisturbed frozen sands to a nearly uniform 38–42% in the seasonally frozen sands (Table 3). Such a change amounts to a maximum subsidence of only 0.2 to 1 m after thawing. The bulk density and void ratios of disturbed and undisturbed sands are also not significantly different and indicate that consolidation has had minimal effect on the upland terrain.

Climate may have been a factor in determining the difference in response of the two sites but it is, however, probably less important than the physical properties of the terrain and sediments. Climatic data for these sites are sparse and discontinuous, but the more coastal and northerly Fish Creek site apparently has a colder climate than the inland East Oumalik site. Mean annual air temperatures (MAT) predicted from mostly summer temperature data for 1978 to 1980 indicate a MAT at Fish Creek of −11.6°C and at East Oumalik of −10.4°C (Haugen and Brown 1980, Haugen pers. comm.*). The thaw season is also generally warmer and longer at East Oumalik so that depth of seasonal thaw is similarly larger. These conditions suggest that a disturbance might cause more rapid and possibly deeper penetration of thaw at East Oumalik.

Thus, following the initial disturbance, terrain modifications at Fish Creek were mainly the result of thaw settlement and consolidation. The apparent one-to-one relationship noted in the intensity of disturbance in 1949 to active layer thickness in 1978 at this site (Lawson et al. 1978) probably results from the inactivity of degradational processes other than thaw settlement. Comparison of the two sites also suggests that the activity of degradational processes had probably diminished within 5 to 10 years after abandonment of the camp at Fish Creek and that further physical changes since that time have been minimal.

Certain of the construction practices used in 1949 at Fish Creek and in 1950 at East Oumalik, such as bulldozing trails and off-road vehicle movement, are generally prohibited in northern permafrost regions of Alaska today. Gravel pads are now used beneath camps and drill rigs, but the long-term effects of these pads are not

*R. Haugen, CRREL, pers. comm. 1981.

known. Other techniques, including excavation and burning of trash, continue to be used (e.g. French 1980). This study suggests that excavations or burning of trash may cause extensive thaw subsidence and other modifications to terrain composed of ice-rich, fine-grained materials such as at East Oumalik, yet will cause much less thaw subsidence with few other effects in ice-poor, coarse-grained materials such as at Fish Creek. Thus, if such techniques are used, they should be sited, when possible, in ice-poor, thaw stable terrain.

DISCUSSION AND CONCLUSIONS

Camp construction and occupation of the East Oumalik upland in 1950 caused an extensive modification of the terrain, drainage, annual depth of thaw, surficial processes and properties of near-surface materials. These modifications were induced by changes in the thermal regime caused by the various activities that took place on the site. Increased ground temperatures resulted in subsidence as the ice-rich, perennially frozen silt of the upland thawed, which subsequently initiated a suite of degradational processes. These processes eroded and removed thawed sediment and meltwater from thaw slopes and depressions. Thawing of undisturbed silt next to subsiding areas led to its failure, mass movement into the depressions and a lateral expansion of physical changes to the upland beyond the area actually disturbed. Some undisturbed areas next to the camp are now being modified, apparently as the result of this lateral migration process.

The primary factors of the near-surface materials and terrain that determined the extent of modification at East Oumalik are 1) ice content, 2) dimensions and distribution of ice wedges and other massive ice, 3) properties of the sediments after thawing, and 4) relief before disturbance, and as modified by thaw subsidence. Thawing of the ice-rich silt produced a sediment with little or no strength that was highly susceptible to failure and erosion. Natural relief on the site, combined with local increases in relief as thaw subsidence took place, were sufficient to cause failure in thawing slopes by gravitational processes and cause meltwater erosion of interconnected thaw depressions. Degradation subsided only after thaw bulb expansion was minimized by reduced availability of meltwater, increased sedimentation in thaw depressions, and changes in slopes.

Analyses of the East Oumalik site suggest that the degradational processes were most active for perhaps 10 to 15 years following disturbance in 1950, with the level of activity and physical modifications to the site decreasing since that time to that of the present. Degradational processes remained active at several locations in and around the site in 1981. The thermal regime is apparently approaching equilibrium with the modified physical condition of the site, but adjustments to the thickness of the active layer are probably continuing. Areas southwest of the original site that are undergoing thaw subsidence are, however, not likely to show cessation of physical changes for about 10 years.

Comparison of the impacts at East Oumalik and Fish Creek, where activities that caused disturbance and length and seasons of occupation were similar, indicates that the types of degradational processes differed and that this difference is directly related to the properties of the perennially frozen sediments and terrain. Fish Creek was not affected as extensively because the upland sand possessed strength in the thawed state and was not highly susceptible to failure or to erosion by meltwater. The lower volume of ground ice and relief minimized both thermal and mechanical erosion by meltwater and the activity of gravitational slope processes. Most modifications of the Fish Creek upland were simply the result of thaw subsidence and consolidation.

The contrast between these sites indicates that geotechnical investigations of areas underlain by perennially frozen ground should include detailed analysis of the in-situ conditions and testing of materials for response during thaw. Determining the texture, ice volume, void ratio, density, water content and liquid limit of the sediment appears to indicate the potential susceptibility of perennially frozen sediments to long-term and extensive impacts after they are disturbed. Further, natural relief of the site combined with changes in elevation and slope due to thaw subsidence determine drainage and affect the type and extent of degradational processes that act upon the thawed sediment.

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